RBEM
Revista Brasileira de Educação Médica

REVIEW ARTICLE

DOI: https://doi.org/10.1590/1981-5271v49.4-2025-0058.ING

Use of 3D printing in the development of knowledge in medical students: an integrative analysis

Uso da impressão 3D no desenvolvimento do conhecimento em estudantes de Medicina: uma análise integrativa

Paula Cristina Yukari Suzaki Fujii[1] paulacysfujii@gmail.com
Guilherme Marçal Ferreira Lima[1] guilherme.lima@aluno.fpp.edu.br
Leonardo Lopes Caetano dos Santos[1] leonardo.santos@aluno.fpp.edu.br
Louise Knauber[1] louise.knauber@aluno.fpp.edu.br
Mariana Xavier e Silva[2] mariana.silva@fpp.edu.br
Izabel Cristina Meister Coelho[1] izabel.coelho@fpp.edu.br
Camila Moraes Marques[1] camilam14@gmail.com

ABSTRACT

Introduction: 3D printing is a tool with several applications in medicine, with wide use for medical education, and can be used for research, education and simulation for students and residents, but with potential still little explored.

Objective: The study aimed to perform an analytical synthesis of the use of 3D printing for knowledge gain among medical students, compared with traditional teaching.

Method: This is an integrative literature review, conducted in the databases ScienceDirect, PubMed and Biblioteca Eletrônica Científica Online (Scielo), in the last 5 years (2020-2024). The descriptors "3D Printing", "Medical Education" and "Engagement Learning" were used in the first database and "3D Printing", "Medical Education" and "Learning" in the second and third database, in Portuguese, English and Spanish, with the Boolean "AND".

Results: The 28 articles selected showed that the use of 3D printing for the construction of knowledge among medical students is an important tool for medical education, providing a deep and meaningful learning, being related to the improvement of short-term learning, higher student satisfaction and engagement compared to traditional teaching methods. The limitations of use are in the availability of materials for printing and limited number of studies for long-term evaluation, there is a need to develop more research.

Conclusion: The use of 3D printing in a strategic and well-structured way is a valuable tool in the development of medical knowledge and skills.

Keywords: Three-Dimensional Printing; Additive Manufacturing; Medical Education; Learning.

RESUMO

Introdução: *A impressão 3D é uma ferramenta com diversas aplicações na medicina, com ampla utilização para o ensino médico, podendo ser utilizada para pesquisas, educação e simulação para estudantes e residentes, mas com potencial ainda pouco explorado.*

Objetivo: *O estudo buscou realizar uma síntese analítica do uso da impressão 3D para o ganho de conhecimento entre estudantes de Medicina, em comparação com o ensino tradicional.*

Método: *Trata-se de uma revisão integrativa de literatura, realizada nas bases de dados ScienceDirect, PubMed e Biblioteca Eletrônica Científica Online (SciELO), nos últimos cinco anos (2020-2024). Foram utilizados os descritores "3D printing", "medical education" e "engagement learning" na primeira base de dados e "3D printing", "medical education" e "learning" na segunda e na terceira base, nos idiomas português, inglês e espanhol, com o booleano "AND".*

Resultado: *De acordo com os 28 artigos selecionados, a impressão 3D para a construção do conhecimento entre estudantes de Medicina apresenta-se como uma importante ferramenta para o ensino médico, oportunizando uma aprendizagem profunda e significativa, estando relacionada à melhoria do aprendizado em curto prazo, à maior satisfação e ao engajamento do aluno em comparação com métodos tradicionais de ensino. As limitações do uso encontram-se na disponibilidade de materiais para impressão e na quantidade limitada de estudos para avaliação em longo prazo, havendo a necessidade de desenvolvimento de mais pesquisas.*

Conclusão: *A impressão 3D utilizada de maneira estratégica e bem estruturada é uma ferramenta valiosa no desenvolvimento do conhecimento e das habilidades médicas.*

Palavras-chave: *Impressão Tridimensional; Manufatura Aditiva; Educação Médica; Aprendizagem.*

[1] Faculdades Pequeno Príncipe, Curitiba, Paraná, Brasil.
[2] Faculdades Pequeno Príncipe, Programa de Pós-Graduação em Ensino nas Ciências da Saúde, Curitiba, Paraná, Brasil.

Chief Editor: Rosiane Viana Zuza Diniz.
Associate Editor: Renata Zappala.

Received on 02/20/25; Accepted 07/02/25.

Evaluated by double blind review process.

INTRODUCTION

Additive manufacturing, commonly known as 3D printing, is a technology that has proved to be an important tool for learning and teaching in medicine. Its uses include surgical applications, which allow for a better understanding of the complex and unique anatomy of each case, reducing costs and optimising surgical strategies[1-6], and its use in the operating and preoperative environment, which potentially reduces operating room procedure time and postoperative length of stay by simulating all the stages in advance, resulting in lower complication rates, a reduction in the reintervention rate and a reduction in healthcare costs[7,8]. In this context, bioprinting is also proving to be an important possibility, enabling the modelling and printing of tissues and organs that can be used for cosmetic, chemical and pharmaceutical tests and organ customisation, representing an opportunity to reduce transplant waiting lists and replace animal models for drug toxicity analysis[7].

As far as medical education is concerned, 3D printing can be used for research, education and simulation for students and residents, being used for surgical training of difficult procedures, operative simulation, better understanding of anatomy and pathology[1-3] and doctor-patient communication7[7,9]. Thus, in view of its innovative nature and impact on medical education, this review sought to develop an analytical synthesis of the use of 3D printing for knowledge gain among medical students, compared to traditional teaching, based on the research question "Can the use of 3D simulators be a strategy to optimise knowledge gain among medical students?".

METHOD

This is an integrative literature review that follows the 6 steps of development according to Mendes et al[10], which consist of: development of the guiding question, search and selection of primary studies, extraction of data from primary studies, critical evaluation of primary studies, synthesis of the results of the review, presentation of the integrative review.

To develop the research question, the acronym "PICO" was used, which stands for Population, Intervention, Comparison and Outcome. Thus, "P" was defined as medical students; "I", the use of 3D simulators; "C", traditional teaching and O, as gaining knowledge. The guiding question was therefore: "Can the use of 3D simulators be a strategy to optimise medical students' knowledge gain?" Three databases were used: ScienceDirect, PubMed and Scientific Electronic Library Online (SciElo).

The first database used the combination "*3d printing AND Medical Education AND Engagement Learning*", while the second and third used "*3d printing AND Medical Education AND Learning*", with descriptors selected from the MeSH (Medical Subject Headings). The search for primary studies was conducted during July 2024.

The inclusion criteria were articles from the last 5 years (2020-2024), in English, Portuguese and Spanish, of the review and original article type, open access, excluding studies that did not answer the research question and duplicates. Eligibility criteria were used according to the PRISMA flowchart. The articles were examined and selected by two independent researchers, according to a standardised procedure. The results obtained were compared and aligned between the researchers. In cases of disagreement, the agreement of other researchers involved in the research was sought.

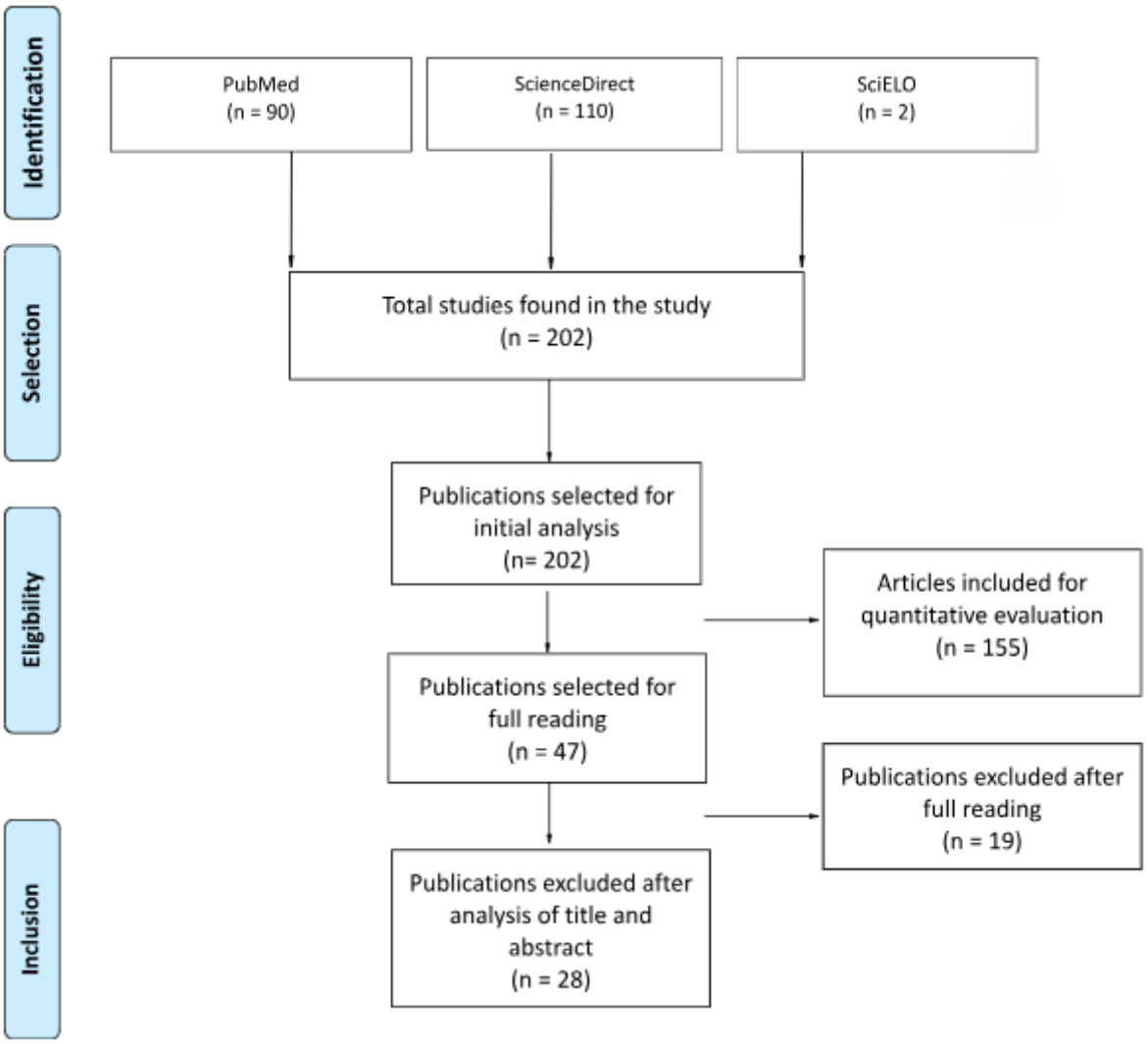
The flowchart below describes the article selection process (Figure 1).

RESULTS

We analysed 28 articles that investigated the use of 3D printing in medical education, highlighting its application in the learning of medical students. The selected studies were conducted in 11 countries – China, Australia, Canada, the United States, Germany, France, Singapore, Chile, Colombia, Ireland and Italy – and published in 11 journals, as detailed in the Chart 1.

The studies mostly covered the use of 3D printing for teaching bone, heart, lung, gynaecological and craniofacial anatomy, studying histology, training in medical procedures and the existence of 3D printing laboratories in health services. The use of 3D printing stands out mainly for understanding injuries and developing competences and practical skills, student engagement and satisfaction and the development of technical skills. All the studies provided significant positive results for the use of 3D printed models for teaching purposes and the findings are summarised in the table below.

Figure 1 PRISMA flowchart for article selection.



Source: Prepared by the authors.

Chart 1. Chart of selected articles by country and journal.

Title of article	Country	Journal (Year)
Make and Break Your Own Hand: A Review of Hand Anatomy and Common Injuries.	United States of America	Journal of Education and Teaching in Emergency Medicine (2020)
Development of a three-dimensional printed heart from computed tomography images of a plastinated specimen for learning anatomy	Singapore	Anatomy and Cell Biology (2020)
Evaluation of a Novel 3D-Printed Urinary Catheterization Simulation Model in Undergraduate Medical Teaching.	Canada	Cureus (2020)
The role of 3D printed models in the teaching of human anatomy: a systematic review and meta-analysis.	China	BMC Medical Education (2020)
The Impact of Three-Dimensional Printed Anatomical Models on First-Year Student Engagement in a Block Mode Delivery.	Australia	Anatomical Sciences Education (2020)
Use of tracheobronchial tree 3-dimensional printed model: does it improve trainees' understanding of segmentation anatomy? A prospective study.	Canada	3D Printing in Medicine (2021)
Three-Dimensional Surface Imaging and Printing in Anatomic Pathology	United States of America	Journal of Pathology Informatics (2021)
Evaluating the Impact of Medical Student Inclusion Into Hands-On Surgical Simulation in Congenital Heart Surgery.	Canada	Journal of Surgical Education (2021)

Continue...

Chart 1. Continuation.

Title of article	Country	Journal (Year)
The Use of 3D Printers in Medical Education with a Focus on Bone Pathology	United States of America	Medical Science Educator (2021)
3D Printing Improves the Effectiveness of Fracture Teaching and Medical Learning: A Comprehensive Scientometric Assessment and Future Perspectives	China	Frontiers in Physiology (2021)
The role of 3D printed heart models in immediate and long-term knowledge acquisition in medical education.	Australia	Reviews in Cardiovascular Medicine (2022)
AEducaAR, Anatomical Education in Augmented Reality: A Pilot Experience of an Innovative Educational Tool Combining AR Technology and 3D Printing.	Italy	International Journal of Environmental Research and Public Health (2022)
The Application of Three-Dimensional Technologies in the Improvement of Orthopedic Surgery Training and Medical Education Quality: A Comparative Bibliometrics Analysis	China	Frontiers in Bioengineering and Biotechnology (2022)
Evaluating a novel 3D printed model for simulating Large Loop Excision of the Transformation Zone (LLETZ)	Germany	3D Printing in Medicine (2022)
Evaluating the value of a 3D printed model for hands-on training of gynecological pelvic examination	Germany	3D Printing in Medicine (2022)
From the ground up: understanding the developing infrastructure and resources of 3D printing facilities in hospital-based settings	United States of America	3D Printing in Medicine (2022)
Three-dimensional printing models improve long-term retention in medical education of pathoanatomy: A randomized controlled study.	France	Clinical Anatomy (2022)
Design and Manufacture of 3D Printed Models as a Complement to Practical Classes in Medical Histology	Chile	International Journal of Morphology (2022)
Hands-On Practice on Sustainable Simulators in the Context of Training for Rural and Remote Practice Through a Fundamental Skills Workshop.	Canada	Cureus (2022)
Students' learning experiences of three-dimensional printed models and plastinated specimens: a qualitative analysis	Singapore	BMC Medical Education (2022)
Utility of 3D Printed Models Versus Cadaveric Pathology for Learning: Challenging Stated Preferences	Australia	Medical Science Educator (2022)
Efficacy of three-dimensional models for medical education: A systematic scoping review of randomized clinical trials.	Colombia	Heliyon (2023)
Evolution in Congenital Cardiology Education: The Rise of Digital-Learning Tools	Ireland	CJC Paediatric and Congenital Heart Disease (2023)
Enhancing medical education in respiratory diseases: efficacy of a 3D printing, problem-based, and case-based learning approach.	China	BMC Medical Education (2023)
An Opportunity to See the Heart Defect Physically: Medical Student Experiences of Technology-Enhanced Learning with 3D Printed Models of Congenital Heart Disease	Australia	Medical Science Educator (2023)
3D printing as a pedagogical tool for teaching normal human anatomy: a systematic review	France	BMC Medical Education (2023)
Evaluation of a 3D-printed hands-on radius fracture model during teaching courses.	Germany	European Journal of Trauma and Emergency Surgery (2024)
Integration of case-based learning and three-dimensional printing for tetralogy of fallot instruction in clinical medical undergraduates: a randomized controlled trial	China	BMC Medical Education (2024)

Source: Prepared by the authors.

Chart 2. Chart summarising the main findings of the selected articles.

Authors (Year)	Summary of the main findings	Method
Sudario *et al.* (2020)	The use of 3D printing to build knowledge of anatomy, injury mechanisms, examination findings and treatment of hand injuries based on practical experience with hand models reinforced knowledge and helped to better identify injuries spatially.	Original article
Radzi *et al.* (2020)	The possibility of anatomic distinction in multi-coloured 3D-printed pieces for studying cardiac anatomy demonstrated significant comprehension compared to monochrome, and is particularly useful for students learning the basics of anatomy.	Original article
Gillis *et al.* (2020)	The 3D printed model allowed the realistic and accurate performance of a urinary catheterization procedure, enabling the students to increase their confidence, competence and knowledge of the technique.	Original article
Ye *et al.* (2020)	The use of 3D printing allows for more effective learning, generating good student satisfaction.	Systematic review and meta-analysis
Tripodi *et al.* (2020)	3D printing for learning upper limb anatomy improved academic performance in tests, increased student engagement with the content and enabled independent learning, improving confidence, reducing anxiety and facilitating study.	Original article
O'Brien *et al.* (2021)	3D printing for the study of tracheobronchial anatomy showed better long-term results compared to the use of 2D images.	Original article (prospective study)
Bois *et al.* (2021)	The use of 3D printing in medical education allows for a better understanding of anatomical studies without the restrictions imposed by biohazardous samples, and can accurately reproduce colours and textures with excellent results if high-quality printers are used.	Original article
Hon *et al.* (2021)	3D printed parts for training in cardiac surgery with student assistance improved surgical skills, interest and understanding of the subject.	Original article
Youman *et al.* (2021)	3D printed models make learning about bone tumours more innovative and effective.	Original article
Shi *et al.* (2021)	3D printing can improve the effectiveness and extent of training in fractures	Literature review
Lau *et al.* (2022)	The use of 3D printing indicated an improvement in the immediate acquisition of knowledge compared to traditional methods for the study of congenital heart disease	Original article
Cercenelli *et al.* (2022)	Studying the anatomy of the skull using 3D printed models allows for a better understanding of anatomical structures and relationships.	Original article
Shi *et al.* (2022)	In the study of orthopaedics, 3D printing makes the learning experience more interesting and is an important tool in promoting teaching.	Literature review
Kiesel *et al.* (2022a)	The use of 3D printed models to teach and train speculum examination, cervical biopsy and curettage, and excision of the transformation zone with a diathermy loop increased students' knowledge, confidence and preparation.	Randomised clinical trial
Kiesel *et al.* (2022b)	3D printed parts to assemble structures for the study of gynaecological anatomy have enabled a deeper understanding and greater retention of the information obtained	Randomised clinical trial
Shine *et al.* (2022)	3D printing laboratories in healthcare systems have enabled their use for educational application through research and simulation among students and residents	Original article
Al-Badri *et al.* (2022)	There was a significant improvement in long-term knowledge retention from the study of 3D printed models for the study of craniofacial anatomy compared to 2D models.	Original article
Toledo-Ordoñez *et al.* (2022)	3D printed models of the glomerular filtration barrier, oesophageal muscle layer and epidermis facilitated the study of histology.	Original article
Siraj *et al.* (2022)	The use of 3D printing to train students in suturing, cricothyroidostomy, episiotomy and intraosseous access procedures allows them to be autonomous and is a practical, sustainable and cost-effective method.	Original article
Radzi *et al.* (2022)	3D printed parts show superior results for learning fundamental anatomical concepts and organs compared to cadaveric anatomical parts	Randomised clinical trial
Nusem *et al.* (2022)	There was less preference for using 3D printing to study cardiac pathologies compared to cadaveric specimens, but greater student involvement with the printed pieces.	Original article

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Chart 2. Continuation.

Authors (Year)	Summary of the main findings	Method
Ardila *et al.* (2023)	3D printing developed learning skills and knowledge among medical students, and there is great satisfaction with the use of this technology.	Scoping review
Windram *et al.* (2023)	On the role of simulation, virtual and augmented reality tools in medical education, it mentions that 3D printing of anatomical models improves students' understanding of complex anatomy.	Original article
Yan *et al.* (2023)	The use of 3D printing combined with pedagogical approaches such as Problem-Based Learning (PBL) and Case-Based Learning (CBL) improves learning about respiratory diseases.	Original article
Luxford *et al.* (2023)	The use of 3D printed models for the study of congenital heart pathologies is associated with a higher level of satisfaction and confidence in the subject.	Original article
Brumpt *et al.* (2023)	3D printed anatomical models are effective tools for teaching anatomy, especially when it comes to reproducing complex anatomical areas and in the early stages of medical school.	Literature review
Neijhoft *et al.* (2024)	The use of a 3D printed model allowed urinary catheterization to be performed in a realistic way, increasing confidence, competence and technical knowledge among students.	Original article
Zhao *et al.* (2024)	The use of 3D printed models improved learning in post-test results and perceived confidence and satisfaction among students who used Case-Based Learning (CBL) to understand Tetralogy of Fallot.	Randomised clinical trial

Source: Prepared by the authors.

DISCUSSION

Using 3D printing in medical education

In recent years, 3D printing has emerged as an innovative tool in healthcare, transforming both medical practice and education. During medical training, this technology provides more interactive and realistic learning compared to traditional methods, enabling students to study anatomical models that are difficult to access, rare or complex with the use of traditional educational resources[11].

3D printing makes it possible to create detailed replicas of anatomical and pathological structures, enriching the learning experience since physical models offer an enhanced visuospatial understanding, which is crucial for assimilating complex anatomies and acquiring motor skills[3,12,13]. The benefits were already consolidated a few years ago[14], showing that 3D printed models surpass traditional methods.

When teaching anatomy, the ability to visualise and handle detailed 3D models, with the possibility of seeing overlapping structures, facilitates identification and deepens understanding, developing visuospatial skills, which are essential for understanding anatomy even on various planes and in different positions[5,15-17].

As well as improving anatomical understanding, 3D printing also promotes pedagogical innovation. The use of this technology complements traditional teaching methods, offering new ways to explore and understand the complexity of the human body, preparing students for the challenges of modern medical practice[15].

Advantages of 3D printing in medical education:

There are many benefits to using rapid prototyping in medical education, including easier access to rare and complex anatomies, the possibility of modelling different physiological and pathological anatomies from image data and the possibility of sharing 3D models between different institutions. The easy sharing of printed copies or even digital files for local printing democratises knowledge, especially in places with difficult access or scarce resources[3,6,18,19].

Also noteworthy are the speed of printing, the low production cost and the precision of the parts compared to the originals[5,20]. In places with limited resources, additive manufacturing allows access to affordable models and tools at a fraction of the cost of traditional methods, allowing for more complete medical training without incurring significant financial burdens, given the reduced costs of printing, equipment, materials and software in recent years[5,22].

It is also known that the use of 3D-printed patient-specific anatomical models can increase performance and promote faster learning among students, improving knowledge, management and confidence, highlighting their benefit in medical education[5,21,22].

The use of high-quality printers also allows for precise reproduction of colours and textures, providing excellent results compared to cadaveric samples, preserving anatomical landmarks and references that are often lost when handling fresh specimens[18]. The possibility of manufacturing in materials of different strengths, densities and colours in the same sample

allows for a more accurate reproduction of printed models and, combined with the feasibility of enlarging and reducing the original size of the parts, makes specific needs more accessible[13]. The ability to make models with removable structures also makes it possible to accentuate anatomical details, improving understanding and visualisation of different parts, supporting greater understanding and learning[13,15,16,18].

When it comes to studying complex organs and structures, visualisation is sometimes difficult, even after dissection, which hinders the study of these parts. The use of 3D printing makes it possible to understand these complex parts of anatomy and pathology, given the possibility of tactile and visual appreciation in 3D, and is more cost-effective than studying cadaveric specimens, which require high costs to obtain, dissect and maintain, or virtual reality environments, which lack important tactile information[13,23].

It should also be noted that in the study of specific pathologies and fractures, the use of cadavers is scarce due to the lack of pathological alterations that make their study possible[24]. Accordingly, rapid prototyping allows for a better understanding of anatomy without the restrictions imposed by the biological risk of cadavers[25]. It is also useful for students who cannot access anatomical study on cadavers due to religious or cultural beliefs or those who have difficulty accessing online resources due to difficulties with communication technology tools[25].

Advances, benefits and applications:

During medical school, the use of 3D printing has been used mainly for the study of anatomy, allowing students to access knowledge in a practical way, facilitating the learning of complex topics and anatomies. In relation to the study of anatomy, studies have discussed the use of this technology to teach regional anatomy of the limbs, neck and organs, as well as cardiovascular, bone, brain, liver and gynaecological structures, in addition to procedural training[12,13,25-28].

Realising the importance of studying bone anatomy for building student knowledge, Neijhoft et al[29] proposed using 3D printing to study radius fractures, together with X-rays and CT scan data. Although no significant differences in learning were found between the methods alone, the evaluations of the printed model were equal to or higher than the other methods. Combinations of methods that included printed models, either with X-rays or CT scans, led to better results. As learning is a unique and personal experience, the combination of visual, auditory and tactile approaches facilitates comprehension and supports lasting retention of the content.

Faced with the challenge of studying gynaecological anatomy and performing the female pelvic examination, Kiesel et al[27] investigated the use of 3D printing in teaching gynaecology. The study involved fifth- and sixth-year medical students, who were given a 3D-printed disassembled model of the female pelvis. The students were instructed to assemble the model to improve their anatomical understanding, since existing models for vaginal examination training often make it difficult to understand anatomical relationships. It was evident that the active involvement of the students in assembling the model contributed to a deeper understanding and greater retention of the information obtained, revealing that encouraging students and giving them the chance to participate in practical learning was viewed positively.

Still regarding the use of rapid prototyping in gynaecology, the same author describes in another study the use of 3D printed models for training medical students in excision of cervical lesions[26]. In this randomised clinical trial, students were asked to simulate a speculum examination, cervical biopsy and curettage, as well as excision of the transformation zone with a diathermy loop. It was found that the students who used the new simulator reported greater preparation and confidence to perform real procedures, subjectively showing a greater degree of technical knowledge of surgery and gynaecological examination[26]. Similarly, Gillis et al[19] evaluated the experience of students after using a printed model to simulate urinary catheterization. Likewise, the results presented showed an increase in self-reported confidence and competence in performing urinary catheter insertion, as well as representing a realistic simulation on an accessible, low-cost simulator.

Training in surgical procedures was also explored by Hon et al[12] in their article in which practical surgical simulation was carried out in congenital heart surgery using 3D printed models. In the research, 15 students were allowed to act as main assistants in cardiac surgeries performed on the models, after undergoing a training session focussed on surgical assistance. The participants reported that the use of the models was useful in learning complex anatomy and understanding the pathophysiology of congenital heart disease. It should also be emphasised that the simulation of the procedure strongly contributed to improving surgical skills, preparing students to better assist in surgeries and increasing their interest in the subject.

In another study, Sudario et al[28] proposed that residents and students develop their knowledge of bone trauma of the extremities with a focus on dislocations/subluxations, fractures, sprains and strains based on the print of the bones of the hand. Based on the print and organisation of the anatomically correct model of the hand, as well as the construction of the functional complexes of flexor and

extensor tendons of the phalanges, the students had practical access to knowledge. This experience led the students to say at the end of the session that practising with the manual models reinforced their knowledge and helped them to better identify lesions spatially. The study emphasises that the construction of the models was especially useful for learning about tendon function and injuries. Although the models had limitations in terms of anatomical functionality, they were still useful for visualising the spatial interaction between bones and tendons[28]. Similarly, the review by Shi et al[24] highlighted the benefits of 3D models for learning and training in relation to fractures, since their simulation brings an environment closer to the real situation, being superior to the use of conventional models and virtual reality.

Tripodi et al[25] explored the use of 3D printing in the teaching of upper limb anatomy to first-year students of Scientific Basis of Osteopathy 1, which includes anatomy, biomechanics and physiology applied to the upper limb. The study, which involved 111 students, provided each of them with a set of 3D printed bones and modelling clay to create muscles and joints. The students were encouraged to take the materials home and repeat the activities, which increased their engagement with the content and practice. At the end of the study, it was reported that the use of the materials increased the students' levels of engagement with the class activities and the content of the unit. This higher ratio was associated with the versatility and tactile and kinaesthetic nature of printed bones, which can be drawn and used to help identify important anatomical landmarks. The study's limitations include the orientation in which the bones were printed, with only one lateral surface provided to the students, and the precision of the anatomical landmarks, which would make it easier to distinguish between the reference points. Despite the benefits found, the review by Shi et al[24] shows that for the study of less complex anatomy such as the upper and lower limbs, as in this study, the teaching effect brought about by 3D printing is not as significant, with the use of two-dimensional CT scans or 3D reconstruction images being sufficient to achieve high-level teaching effects at low cost.

Unlike the other studies on the use of 3D printing to teach macroscopic anatomy, Toledo-Ordoñez et al[30] report on the use of 3D printing to teach histology. In their study, the authors proposed the construction of 3D printed models to complement practical lessons in Histology, in order to provide a better understanding of the glomerular filtration barrier in its physiological state, nephrotic syndrome and the histology of the oesophagus and skin layers. Despite the limitation of not analysing the perception and benefit of using the models in the learning of the students who had access to them, the potential to favour the learning of Histology, the low cost of manufacture and biosafety are reported.

The use of 3D printing has also been utilised in a workshop to train medical students and professionals in rural and remote areas[6]. Using printed models, the participants were able to practise suturing, cricothyrotomy, episiotomy and intraosseous access procedures. The results presented were positive, mainly due to the possibility of student autonomy in printing models, performing practical activities according to individual learning speed, practicality, sustainability and cost reduction, given the high cost of simulators[6].

Impact on student learning and performance:

As regards student learning, student engagement is essential for deep learning, which is associated with greater perceived academic confidence and greater overall satisfaction with undergraduate training[25]. The implementation of deep learning can be effective by encouraging the student to play an essential role in the search for knowledge. This type of learning contrasts with superficial learning, in which the student simply memorises facts and content without any real applications or purposes, which occurs when the educator is the presenter of knowledge and the student is the consumer. The latter method predisposes students to less engagement with the content and the classroom, leading to poorer results[25].

The use of 3D printing makes it possible to improve and complement forms of learning, allowing for a deeper and more meaningful understanding. Yan et al[4], in their study with 442 medical students, compared the use of 3D printing associated with Problem-Based Learning and Case-Based Learning with traditional methods for learning about respiratory diseases. The students with access to the 3D printed model and group discussions scored higher in the post-test assessments of the lesson, but showed similar results in the main assessment on the subject two weeks later. This suggests that there is little advantage in maintaining theoretical knowledge compared to the traditional methodology. However, the students who had access to the printed model had higher self-assessment and satisfaction scores in terms of clinical thinking, learning initiative, mastery of anatomical knowledge, confidence in learning, ability to analyse and solve problems, understanding of knowledge and level of satisfaction with the teaching method.

Comparing the use of 3D printing between two groups using Case-Based Learning for understanding Tetralogy of Fallot, Zhao et al[31] found that the use of the printing revealed significant improvements in post-test performance, particularly in pathological anatomy and interpretation of image data. In addition, students showed higher levels of satisfaction and confidence compared to students who did not have access

to 3D printed models, highlighting the positive impact of incorporating them into the learning environment.

Youman et al[32], in another study comparing osteochondroma and osteosarcoma learning among first-year medical students, using 2D images and 3D printed models, found no better scores compared to the groups using 2D images and 3D models. However, similar to the previous study, the students considered the learning activity to be "effective" and "innovative", revealing that the use of 3D printing can make learning even more meaningful, corroborating the results of other studies in which the 3D printing groups took less time to answer the questions compared to the conventional groups[21].

This result corroborates other studies on the use of prototyped models to study complex cardiac pathologies[12,13] and reviews on the effectiveness of three-dimensional models for medical education[5,21,22]. These studies show that involving students in models increases their satisfaction, motivation and confidence in learning, allowing them to retain knowledge more deeply and improve their skills[5,12,13,21,22].

Tripodi et al[25] also reported that using 3D printed materials to study anatomy reduced anxiety levels. Since it was possible to study with the bones outside of the university and class time, there was greater autonomy for learning, leading to improved performance and increased interest. Among the students, it was emphasised that being able to look at and touch the models made learning more effective than just reading, studying slides and looking at pictures.

When it comes to evaluating student learning and gaining knowledge, other studies also corroborate the advantage of additive manufacturing for teaching students in the early stages of the course, such as the study by Radzi et al[33] and Radzi et al[34]. In the first, the author compares the knowledge gained by using 3D printing compared to cadaveric anatomical specimens for the study of cardiac and head and neck anatomy. The results of the printed parts were superior for learning fundamental anatomical concepts and organs, while the cadaveric parts were considered more suitable for studying complex regions. In the second, the author also highlights the possibility of distinguishing anatomy in colour, having demonstrated a significantly better understanding of the participants in multi-coloured models compared to monochrome ones, being particularly useful for students learning the basics of anatomy.

Similarly, comparing cadaveric parts to 3D printed models for the study of cardiac anatomy, Nusem et al[19] found the benefit of greater student involvement, as they tend to manipulate the printed parts more, without the fear of causing damage. However, unlike other studies, there was a slight initial preference for cadaver hearts over 3D printed hearts. Lim et al[35], in an older study, corroborates the findings and points out that the use of anatomically accurate 3D parts can serve as a useful basis for inducing familiarity, facilitating comfort levels and breaking down psychological inhibitions to the eventual use of cadavers. The use of such a tool can overcome barriers that often limit learning, such as apprehension, significant stress and anxiety during initial encounters with cadavers, as well as the initial tendency to avoid contact with cadaveric material among students at an early stage.

Challenges, Limitations and Future Directions:

It should be noted that 3D printing is not restricted to the anatomical, histological or microscopic study of parts. Shine et al[2] point out in their study on 3D printing facilities in healthcare systems that the existence of such facilities supports access to printing, taking into account the extensive utility of 3D printing in healthcare. In most facilities, a multidisciplinary team works, usually led by physicians, followed by engineers and in some cases by students, developing leadership and teamwork skills in the participants.

It has been suggested that training with technical skills in 3D modelling and printing can improve spatial ability, develop critical thinking and encourage creativity[5], reinforcing the importance not only of the ease of the parts, but also of the whole process involved in 3D printing in medical education. Accordingly, the skills developed in these facilities are extremely relevant, as they allow students to manufacture from design to printing the final model.

Another interesting point is the involvement and scientific output of the groups, with papers published and presented at medical, additive manufacturing and innovation congresses[2]. For the student's academic training, the existence of these facilities allows the student not only to learn about 3D printing, but also to have contact with the multidisciplinary team, reinforcing the basic tripod of universities: teaching, research and outreach[36].

Currently, one of the main limitations of 3D printing is the cost and availability of printing materials. Printed parts can sometimes lack flexibility or have a lower tactile quality compared to real parts, and there are only a few materials with elastic properties that resemble human tissue, which would be ideal for printing specific training models and, when available, costs are a major impediment[16].

The ethical implications of printed models also stand out, given the storage of files for printing organs or foetal prototypes and the possible sharing of data. Without the donor's permission, 3D printing the body or even its parts can lead to an ethically questionable lack of consent, making the

situation even more worrying in the case of selling the models or print files for profit[21].

It is believed that, in the future, printed materials designed to imitate "softer" tissues will have to be manufactured by combining components in order to imitate the biomechanical properties of tissues and structures as much as possible, as suggested by older studies[8,37]. It is hoped that further research on the subject will allow 3D printing not only to achieve anatomical fidelity, but also tissue fidelity.

Another significant limitation and question in relation to the use of 3D printing in medical education is the use and impact of learning through 3D models[38]. Although the studies provide questions and practical tests to assess students' knowledge pre- and post-test for assessment, these methods still have limitations on the use and place of 3D printing in the medical curriculum and the impact of its use on student learning, especially in the long-term evaluation of the use of models.

In one of the few studies evaluating immediate and long-term knowledge acquisition among students who used 3D printing compared to traditional methods for studying congenital heart disease, Lau et al[11] found that the use of 3D printing indicated an improvement in immediate knowledge acquisition, but at the same time, they also found that students who used 3D printing performed slightly less well than the control group in long-term knowledge retention, with both results having little statistical relevance. Therefore, the results of the study did not suggest any significant improvement in the acquisition and retention of knowledge when using 3D printing compared to conventional teaching methods. Despite the results, the study shows that the positive benefits of 3D printing in improving the learning experience should not be overlooked, and further research is needed.

In another study that also assesses this long-term impact, Al-Badri et al[39] evaluated long-term knowledge retention for the study of craniofacial anatomy using 3D printed models. As a result, it was found that 3D printed models of spatially complex structures, such as various craniosynostosis patterns, significantly improved the long-term retention of medical students, indicating their educational effectiveness.

O'Brien et al[23], evaluating the long-term retention of knowledge about tracheobronchial anatomy, compared students who studied for 20 minutes with 3D printed models to those who only used 2D images. After two weeks, the students who used printed models maintained their level of knowledge, while the group that used 2D images showed a drop in their scores. Although the 2D imaging group showed slightly better performance immediately after the study, the difference was not significant. These results suggest that students retain more information using visual and tactile learning methods than using conventional textbooks or 2D-based learning. However, there were limitations in relation to the sample, as the study only involved 31 students, so caution is needed when interpreting and generalising the data.

Given the limited number of studies, the discrepancies found and the growing interest in 3D anatomy models, there is a need for further research focussing on evaluating knowledge retention and the long-term effectiveness of using 3D models, especially assessing the lasting impact of 3D printing on knowledge gain.

For a more in-depth assessment of the impact of 3D printing on student knowledge, future studies need to include larger samples and compare the use of 3D printing with traditional teaching methods, using appropriate control groups. This comparative approach will help to outline the specific benefits and possible limitations of 3D technology compared to conventional practices.

Finally, to effectively integrate this tool into medical curricula and develop new research, it is essential to implement training programmes for educators. These programmes should train teachers in the use and integration of 3D printing into the medical curriculum, ensuring that the benefits of this technology are fully exploited in the education of future health professionals.

Limitations

This research has some limitations. Firstly, the selection of articles restricted to open access publications may have excluded relevant studies published in paid journals. The delimitation of languages to Portuguese, English and Spanish could potentially have excluded important contributions in other languages. Restricting the publication period to the last five years may also have omitted older studies that are still relevant to the subject.

Another significant limitation is the variability in the methods and parameters of the studies reviewed, which can make direct comparisons and the generalisation of results difficult. The lack of uniformity in the evaluation criteria and study models used prevents a more consistent analysis of the impact of 3D printing on the development of knowledge among medical students.

Most of the available studies focus on the short-term evaluation of the impact of 3D printing on medical education. There is a dearth of research investigating the long-term effects, including knowledge retention and the practical application of acquired skills. This highlights the need for future studies to address these issues and provide a more comprehensive view of the benefits and limitations of 3D printing in medical education.

CONCLUSION

The use of 3D printing to build knowledge among medical students is associated with deep and meaningful learning and is related to improved learning in the short term, greater student satisfaction and engagement compared to traditional teaching methods. However, there are limitations to its use, mainly in the availability of printing materials and the limited number of studies for long-term evaluation. It is therefore essential to invest in research, infrastructure and training for educators to maximise the impact and integrate this technology effectively into the medical curriculum.

ACKNOWLEDGMENTS

We would like to thank Faculdades Pequeno Príncipe and the Araucária Foundation to Support Scientific and Technological Development in the State of Paraná for making it possible to conduct this research through a Scientific Initiation project.

CONTRIBUTION OF THE AUTHORS

Paula Cristina Yukari Suzaki Fujii, Guilherme Marçal Ferreira Lima, Leonardo Lopes Caetano dos Santos and Louise Knauber contributed to the conception of the study, project methodology, data analysis and writing the project. Mariana Xavier e Silva, Camila Marques and Izabel Cristina Meister Coelho contributed to the conception of the study, project methodology, supervision, review and editing.

CONFLICT OF INTEREST

We declare no conflict of interest.

FUNDING

Araucária Foundation to Support the Scientific and Technological Development of the State of Paraná, TC # 209/2022 PDI.

DECLARATION OF DATA AVAILABILITY

Research data is available in the body of the document.

REFERENCES

1. Perica E, Sun Z. Patient-specific three-dimensional printing for pre-surgical planning in hepatocellular carcinoma treatment. Quant Imaging Med Surg. 2017 Dec;7(6):668-77. doi: https://doi.org/10.21037/qims.2017.11.02.
2. Shine KM, Schlegel L, Ho M, Boyd K, Pugliese R. From the ground up: understanding the developing infrastructure and resources of 3D printing facilities in hospital-based settings. 3D Print Med. 2022 July 11;8(1):21. doi: https://doi.org/10.1186/s41205-022-00147-7.
3. Windram JD, Neal A, McMahon CJ. Evolution in congenital cardiology education: the rise of digital-learning tools. CJC Pediatr Congenit Heart Dis. 2022 Dec 28;2(2):93-102. doi: https://doi.org/10.1016/j.cjcpc.2022.12.005.
4. Yan X, Zhu Y, Fang L, Ding P, Fang S, Zhou J, et al. Enhancing medical education in respiratory diseases: efficacy of a 3D printing, problem-based, and case-based learning approach. BMC Med Educ. 2023 July 17;23(1):512. doi: https://doi.org/10.1186/s12909-023-04508-6.
5. Ardila CM, González-Arroyave D, Zuluaga-Gómez M. Efficacy of three-dimensional models for medical education: a systematic scoping review of randomized clinical trials. Heliyon. 2023 Feb 1;9(2):e13395. doi: https://doi.org/10.1016/j.heliyon.2023.e13395.
6. Siraj S, Sivanathan M, Abdo S, Micallef J, Gino B, Buttu D, et al. Hands-on practice on sustainable simulators in the context of training for rural and remote practice through a fundamental skills workshop. Cureus. 2022 Sept 6;14(9):e28840. doi: https://doi.org/10.7759/cureus.28840.
7. Aimar A, Palermo A, Innocenti B. The role of 3D printing in medical applications: a state of the art. J Healthc Eng. 2019 Mar 21;2019(10):1-10. doi: https://doi.org/ 10.1155/2019/5340616.
8. Garcia J, Yang Z, Mongrain R, Leask RL, Lachapelle K. 3D printing materials and their use in medical education: a review of current technology and trends for the future. BMJ Simul Technol Enhanc Learn. 2018 Jan;4(1):27-40. doi: https://doi.org/10.1136/bmjstel-2017-000234.
9. Sanchez AU, Silva AMS, Heilmann RM, Tube MIC, Almeida MBV, Rolim Filho EL. Impressão 3D na relação médico-paciente: relato de experiência da integração entre ensino, inovação e assistência. Rev Bras Educ Med. 2024;48(3):e083,2024. doi: https://doi.org/10.1590/1981-5271v48.3-2023-0012.
10. Mendes KS, Silveira RC, Galvão CM. Revisão integrativa: método de pesquisa para a incorporação de evidências na saúde e na enfermagem. Texto Contexto Enferm. 2008;17(4):758-64. doi: https://doi.org/10.1590/S0104-07072008000400018.
11. Lau I, Sun Z. The role of 3D printed heart models in immediate and long-term knowledge acquisition in medical education. Rev Cardiovasc Med. 2022 Jan 17;23(1):022. doi: https://doi.org/10.31083/j.rcm2301022.
12. Hon NWL, Hussein N, Honjo O, Yoo SJ. Evaluating the impact of medical student inclusion into hands-on surgical simulation in congenital heart surgery. J Surg Educ. 2021 Jan-Feb;78(1):207-13. doi: https://doi.org/10.1016/j.jsurg.2020.06.023.
13. Luxford JC, Cheng TL, Mervis J, Anderson J, Clarke J, Croker S, et al. An opportunity to see the heart defect physically: medical student experiences of technology-enhanced learning with 3D printed models of congenital heart disease. Med Sci Educ. 2023 Aug 1;33(5):1095-107. doi: https://doi.org/10.1007/s40670-023-01840-w.
14. Preece D, Williams SB, Lam R, Weller R. "Let's get physical": advantages of a physical model over 3D computer models and textbooks in learning imaging anatomy. Anat Sci Educ. 2013 July-Aug;6(4):216-24. doi: https://doi.org/10.1002/ase.1345.
15. Cercenelli L, De Stefano A, Billi AM, Ruggeri A, Marcelli E, Marchetti C, et al. AEducaAR, Anatomical Education in Augmented Reality: a pilot experience of an innovative educational tool combining AR technology and 3D printing. Int J Environ Res Public Health. 2022 Jan 18;19(3):1024. doi: https://doi.org/10.3390/ijerph19031024.
16. Brumpt E, Bertin E, Tatu L, Louvrier A. 3D printing as a pedagogical tool for teaching normal human anatomy: a systematic review. BMC Med Educ. 2023 Oct 20;23(1):783. doi: https://doi.org/10.1186/s12909-023-04744-w.
17. Shah K, Ahmed J, Shenoy N. How different are students and their learning styles? Int J Res Med Sci. 2013 July;1(3):1. doi: https://doi.org/10.5455/2320-6012.ijrms20130808.
18. Bois MC, Morris JM, Boland JM, Larson NL, Scharrer EF, Aubry MC, et al. Three-dimensional surface imaging and printing in anatomic pathology. J Pathol Inform. 2021 May 18;12:22. doi: https://doi.org/10.4103/jpi.jpi_8_21.
19. Nusem E, Bray L, Lillia J, Schofield L, Scott KM, Gunasekera H, et al. Utility of 3D printed models versus cadaveric pathology for learning: challenging stated preferences. Med Sci Educ. 2022 Nov 16;32(6):1513-20. doi: https://doi.org/10.1007/s40670-022-01684-w.
20. Gillis CJ, Bishop N, Walsh G, Harvey D. Evaluation of a novel 3D-printed urinary catheterization simulation model in undergraduate medical teaching. Cureus. 2020 May 31;12(5):e8377. doi: https://doi.org/10.7759/cureus.8377.
21. Ye Z, Dun A, Jiang H, Nie C, Zhao S, Wang T, et al. The role of 3D printed models in the teaching of human anatomy: a systematic review and meta-analysis. BMC Med Educ. 2020 Sept 29;20(1):335. doi: https://doi.org/10.1186/s12909-020-02242-x.

22. Shi J, Cavagnaro MJ, Xu S, Zhao M. The application of three-dimensional technologies in the improvement of orthopedic surgery training and medical education quality: a comparative bibliometrics analysis. Front Bioeng Biotechnol. 2022 Mar 22;10:852608. doi: https://doi.org/10.3389/fbioe.2022.852608.

23. O'Brien C, Souza CA, Sheikh A, Miguel O, Wood T. Use of tracheobronchial tree 3-dimensional printed model: does it improve trainees' understanding of segmentation anatomy? A prospective study. 3D Print Med. 2021 Jan 6;7(1):2. doi: https://doi.org/10.1186/s41205-020-00092-3.

24. Shi J, Fu S, Cavagnaro MJ, Xu S, Zhao M. 3D printing improve the effectiveness of fracture teaching and medical learning: a comprehensive scientometric assessment and future perspectives. Front Physiol. 2021 Dec;12:726591. doi: https://doi.org/10.3389/fphys.2021.726591.

25. Tripodi N, Kelly K, Husaric M, Wospil R, Fleischmann M, Johnston S, et al. The impact of three-dimensional printed anatomical models on first-year student engagement in a block mode delivery. Anat Sci Educ. 2020 Nov;13(6):769-77. doi: https://doi.org/10.1002/ase.1958.

26. Kiesel M, Beyers I, Kalisz A, Wöckel A, Löb S, Schlaiss T, et al. Evaluating a novel 3D printed model for simulating Large Loop Excision of the Transformation Zone (LLETZ). 3D Print Med. 2022a Jun 8;8(1):15. doi: 10.1186/s41205-022-00143-x.

27. Kiesel M, Beyers I, Kalisz A, Wöckel A, Quenzer A, Schlaiß T, et al. Evaluating the value of a 3D printed model for hands-on training of gynecological pelvic examination. 3D Print Med. 2022b July 6;8(1):20. doi: 10.1186/s41205-022-00149-5.

28. Sudario G, Wray A, Janson R. Make and break your own hand: a review of hand anatomy and common injuries. J Educ Teach Emerg Med. 2020 Jan 15;5(1):SG1-SG16. doi: https://doi.org/10.21980/J8PH0Z.

29. Neijhoft J, Sterz J, Rüsseler M, Britz V, Bepler L, Freund V, et al. Evaluation of a 3D-printed hands-on radius fracture model during teaching courses. Eur J Trauma Emerg Surg. 2024 Feb;50(1):49-57. doi: https://doi.org/10.1007/s00068-023-02327-4.

30. Toledo-Ordoñez I, Oneto N, Concha M, Sanhueza S, Osses M, Padilla-Meza J, et al. Diseño y fabricación de modelos impresos en 3D como complemento para las clases prácticas de histología médica. Int J Morphol. 2022;40(2):355-9. doi: https://doi.org/10.4067/S0717-95022022000200355.

31. Zhao J, Gong X, Ding J, Xiong K, Zhuang K, Huang R, et al. Integration of case-based learning and three-dimensional printing for tetralogy of fallot instruction in clinical medical undergraduates: a randomized controlled trial. BMC Med Educ. 2024 May 24;24(1):571. doi: https://doi.org/10.1186/s12909-024-05583-z.

32. Youman S, Dang E, Jones M, Duran D, Brenseke B. The use of 3D printers in medical education with a focus on bone pathology. Med Sci Educ. 2021 Feb 24;31(2):581-88. doi: https://doi.org/10.1007/s40670-021-01222-0.

33. Radzi S, Tan HKJ, Tan GJS, Yeong WY, Ferenczi MA, Low-Beer N, et al. Development of a three-dimensional printed heart from computed tomography images of a plastinated specimen for learning anatomy. Anat Cell Biol. 2020 Mar;53(1):48-57. doi: https://doi.org/10.5115/acb.19.153.

34. Radzi S, Chandrasekaran R, Peh ZK, Rajalingam P, Yeong WY, Mogali SR. Students' learning experiences of three-dimensional printed models and plastinated specimens: a qualitative analysis. BMC Med Educ. 2022 Sept 28;22(1):695. doi: https://doi.org/10.1186/s12909-022-03756-2.

35. Lim KH, Loo ZY, Goldie SJ, Adams JW, McMenamin PG. Use of 3D printed models in medical education: a randomized control trial comparing 3D prints versus cadaveric materials for learning external cardiac anatomy. Anat Sci Educ. 2016 May 6;9(3):213-21. doi: https://doi.org/10.1002/ase.1573.

36. Moita FMGSC, Andrade FCB. Ensino-pesquisa-extensão: um exercício de indissociabilidade na pós-graduação. Rev Bras Educ. 2009;14(41):269-80. doi: https://doi.org/10.1590/S1413-24782009000200006.

37. Waran V, Narayanan V, Karuppiah R, Owen SL, Aziz T. Utility of multimaterial 3D printers in creating models with pathological entities to enhance the training experience of neurosurgeons. J Neurosurg. 2014 Feb;120(2):489-92. doi: https://doi.org/10.3171/2013.11.JNS131066.

38. Azer SA, Azer S. 3D anatomy models and impact on learning: a review of the quality of the literature. Health Prof Educ. 2016 Dec;2(2):80-98. doi: https://doi.org/10.1016/j.hpe.2016.05.002.

39. Al-Badri N, Touzet-Roumazeille S, Nuytten A, Ferri J, Charkaluk ML, Nicot R. Three-dimensional printing models improve long-term retention in medical education of pathoanatomy: A randomized controlled study. Clin Anat. 2022 July;35(5):609-15. doi: https://doi.org/10.1002/ca.23878.